Variations & Defects: Influence on Performance & Safety of Aerospace Missions

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Systems Health and Safety

- Overall Goal:
  - Determining sources of normal and abnormal statistical variation for helicopter transmission vibrations
- Current Application:
  - HUMS technologies for helicopters
- Design & Mfg Research Hypothesis:
  - Statistical variation due to D&M is a significant source of unreliability and eventual failures of systems

SHAS Group Research Objectives

- Develop empirical database for modeling & evaluation.
  - ARC data from multiple aircraft: Cobra, Kiowa, Black Hawk.
  - GRC data from transmission and gear test facilities.
- Identify/model factors that influence vibrations.
  - Normal — mfg, installation, operation, maintenance.
  - Abnormal — defects, installation errors, damage, etc.
- Develop algorithms for damage detection.
  - Identify and remove known process and noise effects.
  - Appropriate feature selection and efficient algorithm coding.
- Determine "hit" and "false alarm" rates.
  - Sparse "damage-" signal distributions.
  - Techniques for estimating damage signal distributions.
- Fundamentals of transmission vibrations.
  - First principles modeling — finite element.
  - Gear dynamics modeling — differential equations.

Ames Research Center

On-going Variation Research

- Operational Variations (joint work w/ Ed Huff):
  - Statistical comparison of different helicopters and rigs
  - Analysis of various variation sources
  - Methods to account for baseline changes
  - Metrics to monitor baseline variations & false alarms
- Design & Manufacturing Variations:
  - Empirical correlation between mfg errors and vibrations
  - Modeling of manufacturing effect on performance
  - Modeling of variation sources in design
  - Propagation of design variations to model performance
  - Function-failure correlation/analytical method

Operational Variations: Helicopter Transmissions

- Flight Experiments:
  - Experiment design to test statistical variation during flight for the AH-1 and OH-58 helicopters (Ames, Healthwatch-I)
  - Free flight tests for both helicopters for online false alarm evaluation (Ames, Healthwatch-II)
- Test Rig Experiments:
  - Statistical variation in an Oh58 test rig (Glenn)
  - Normal and abnormal statistical variation in the MFS (Ames)
  - Current experiments being implemented the OH58 test rig for crack detection (Glenn)

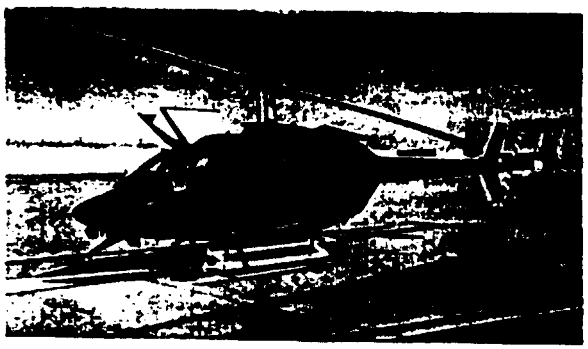
List of Flight Maneuvers

Maneuver	Name	Symbol	Description
A	Forward Flight, Low Speed	FFLS	Fly straight, level, & forward at ~ 20 kts.
B	Forward Flight, High Speed	FFHS	Fly straight, level, & forward at ~ 60 kts.
C	Sideward Flight Left	SL	Fly straight, level, & sideward left.
D	Sideward Flight Right	SR	Fly straight, level, & sideward right.
E	Forward Climb, Low Power	FCLP	Fly forward, straight, & climb at 40 psi.
F	Forward Descent, Low Power	FDLP	Fly forward, straight, & descend at 10 psi.
G	Flat Pitch on Ground	G	Vehicle on ground skids.
H	Hover	H	Stationary hover.
I	Hover Turn Left	HTL	Level hover, turning left.
J	Hover Turn Right	HTR	Level hover, turning right.
K	Coordinated Turn Left	CTL	Fly level, forward, & turning left.
L	Coordinated Turn Right	CTR	Fly level, forward, & turning right.
M	Forward Climb, High Power	FCHP	Fly forward, straight, & climb at 50 psi.
N	Forward Descent, High Power	FDHP	Fly forward, straight, & descend at 50 psi.

Experiment Design for Flights

		Obs. Order	Ground & Hover		Primary Flight Maneuvers						Hover & Ground	
Pilot 1	Flight 1	1	G	H	A	B	C	D	E	F		
		2			B	C	D	E	F	A		
		3			C	D	E	F	A	B	H	G
	Flight 2	1	G	H	I	J	K	L	M	N		
		2			J	K	L	M	N	I		
		3			K	L	M	N	I	J	H	G
Pilot 2	Flight 3	1	G	H	D	E	F	A	B	C		
		2			E	F	A	B	C	D		
		3			F	A	B	C	D	E	H	G
	Flight 4	1	G	H	L	M	N	I	J	K		
		2			M	N	I	J	K	L		
		3			N	I	J	K	L	M	H	G

Variation Study Results: AH-1



Source of Variation		PC-1		PC-2		PC-3	
	df	Sum of Squares	Percent Total SS	Sum of Squares	Percent Total SS	Sum of Squares	Percent Total SS
Covariates	8	558.778	91.40 *	10.977	27.85 *	0.018	1.97
TORQUE	1	554.282	90.66 *	0.007	0.02	0.003	0.33
RATE OF CLIMB	1	0.552	0.09 *	7.690	19.51 *	0.000	0.00
PITCH ANGLE	1	2.832	0.46 *	2.028	5.15 *	0.003	0.33
AIRSPEED	1	0.165	0.03 *	0.061	0.15 *	0.001	0.11
ALTITUDE	1	0.030	0.00	0.095	0.24 *	0.003	0.33
BANK ANGLE	1	0.125	0.02	0.214	0.54 *	0.002	0.22
HEADING	1	0.643	0.11 *	0.221	0.56 *	0.001	0.11
ROTOR RPM	1	0.148	0.02 *	0.661	1.68 *	0.005	0.55 *
Main Effects	21	27.497	4.50 *	25.143	63.80 *	0.171	18.75 *
MANEUVER	12	26.092	4.27 *	24.938	63.28 *	0.139	15.24 *
ORDER	2	0.504	0.08 *	0.010	0.03	0.017	1.86 *
PILOT	1	0.024	0.00	0.185	0.47 *	0.003	0.33
SET	1	0.818	0.13 *	0.000	0.00	0.004	0.44 *
REPLICATION	5	0.059	0.01	0.010	0.03	0.007	0.77
2-Way Interactions	133	9.239	1.51 *	1.313	3.33 *	0.297	32.57 *
MANEUVER ORDER	24	4.771	0.78 *	0.425	1.08 *	0.047	5.15 *
MANEUVER PILOT	12	1.254	0.21 *	0.134	0.34 *	0.098	10.75 *
MANEUVER SET	12	0.823	0.13 *	0.529	1.34 *	0.071	7.79 *
MANEUVER REP	60	1.014	0.17	0.133	0.34	0.051	5.59 *
ORDER PILOT	2	0.119	0.02	0.012	0.03	0.000	0.00
ORDER SET	2	0.133	0.02	0.007	0.02	0.007	0.77 *
ORDER REP	10	0.126	0.02	0.014	0.04	0.006	0.66
PILOT SET	1	0.204	0.03 *	0.017	0.04	0.005	0.55 *
PILOT REP	5	0.098	0.02	0.012	0.03	0.004	0.44
SET REP	5	0.030	0.00	0.025	0.06	0.006	0.66
Explained	162	595.514	97.41	37.433	94.99	0.485	53.18
Residual	767	15.858	2.59	1.976	5.01	0.427	46.82
Total	929	611.371	100.00	39.409	100.00	0.912	100.00

Flight Stationarity Analysis AH-1 vs. OH-58 helicopters

Percent Stationarity by Maneuver
(Planetary Accelerometer A)

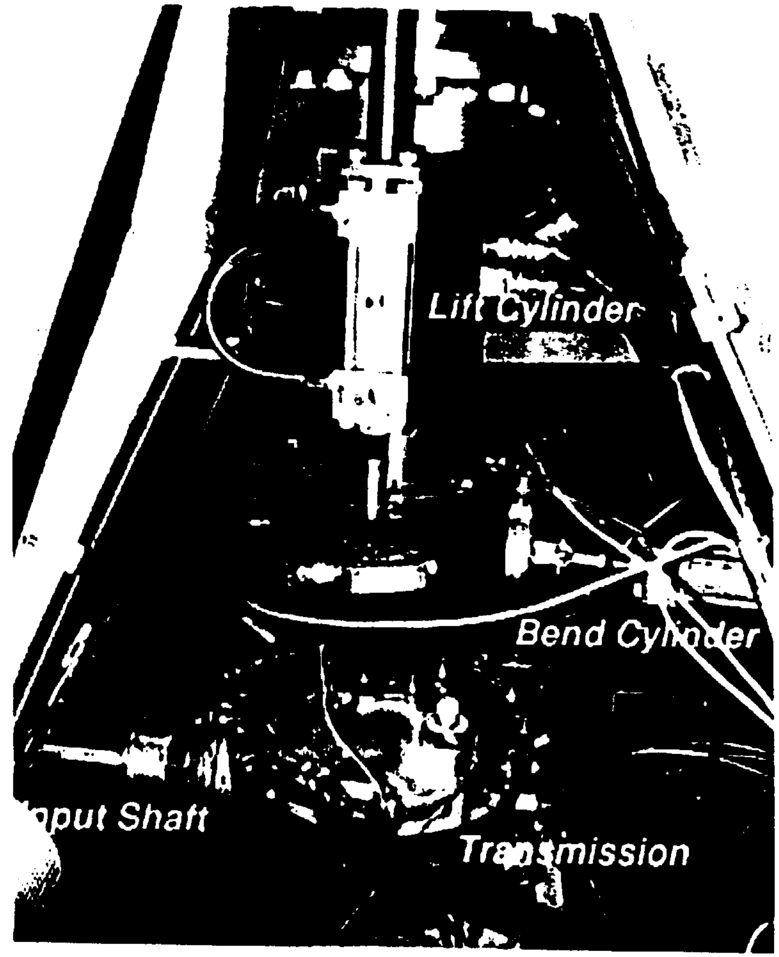
MANEUVER	PERCENT STATIONARY RECORDS	
	OH-58 Kiowa	AH-1 Cobra
A. Forward Flight, Low Speed	70.8%	55.6%
B. Forward Flight, High Speed	65.3%	61.1%
C. Sideward Flight Left	12.5%	22.2%
D. Sideward Flight Fight	9.7%	31.9%
E. Forward Climb, Low Power	50.0%	97.0%
F. Forward Descent, Low Power	16.7%	68.1%
H. Hover	30.2%	80.2%
I. Hover Turn Left	11.1%	59.7%
J. Hover Turn Right	15.3%	36.1%
K. Coordinated Turn Left	79.2%	80.6%
L. Coordinated Turn Right	83.3%	80.6%
M. Forward Climb, High Power	65.3%	86.1%
N. Forward Descent, High Power	22.2%	72.2%
Average Stationarity	40.6%	64.2%

Flight Data Comparison

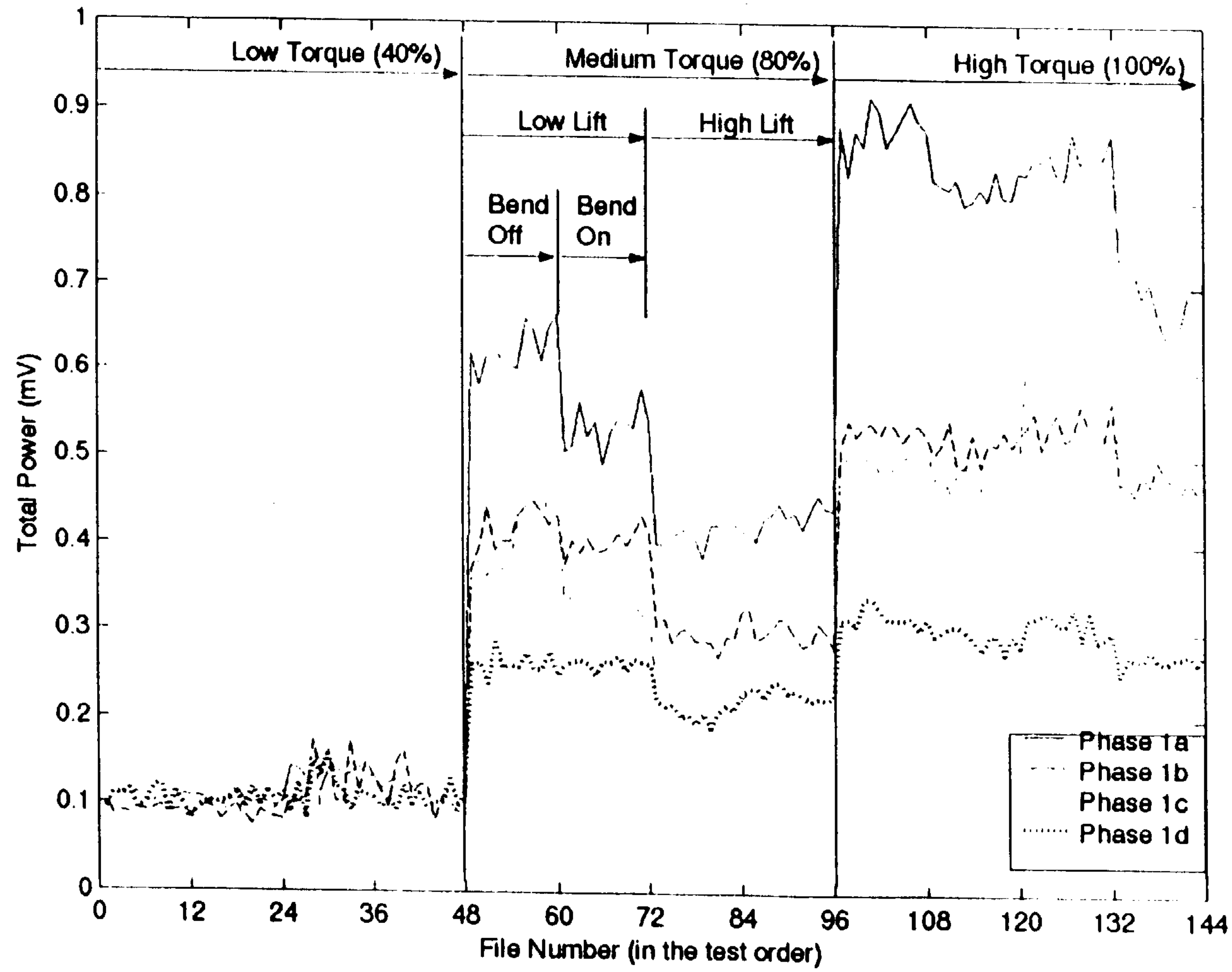
Combined Sources	OH-58 Kiowa Sum of Squares (SS)	OH-58 Kiowa Percent Total SS	OH-58 Kiowa Percent Corrected Total SS	AH-1 Cobra Sum of Squares (SS)	AH-1 Cobra Percent Total SS	AH-1 Cobra Percent Corrected Total SS
PC-1						
Covariates	83.355	61.66		555.872	90.94	
Main Effects	24.461	18.10	47.20	29.261	4.79	52.85
2-Way Interactions	10.212	7.55	19.71	9.787	1.60	17.68
3-Way Interactions	10.845	8.02	20.93	9.356	1.53	16.90
Model	128.873	95.34		604.276	98.86	
Residual Error	6.303	4.66	12.16	6.965	1.14	12.58
Total	135.176	100.00	100.00	611.241	100.00	100.00
PC-2						
Covariates	0.185	0.47		0.198	0.49	
Main Effects	31.873	80.72	81.10	37.398	92.03	92.48
2-Way Interactions	2.838	7.19	7.22	1.174	2.89	2.90
3-Way Interactions	2.550	6.46	6.49	1.095	2.69	2.71
Model	37.446	94.83		39.866	98.10	
Residual Error	2.041	5.17	5.19	0.773	1.90	1.91
Total	39.487	100.00	100.00	40.638	100.00	100.00
PC-3						
Covariates	0.291	6.16		0.285	16.12	
Main Effects	0.855	18.11	19.30	0.738	41.74	49.76
2-Way Interactions	1.530	32.41	34.54	0.340	19.23	22.93
3-Way Interactions	1.481	31.37	33.43	0.224	12.67	15.10
Model	4.158	88.07		1.587	89.76	
Residual Error	0.563	11.93	12.71	0.181	10.24	12.20
Total	4.721	100.00	99.98	1.768	100.00	100.00
Grand Total	179.384			653.647		

OH58 Test Rig Experiments

- determine vibration changes at input pinion due to forces assumed to operate during maneuvering:
  - *Torque*
  - *Mast Lifting*
  - *Mast Bending*
- determine influence of maintenance on vibrations, independent of maneuvering effects.
  - *Reconfiguration*



OH58 Test Rig: Analysis Results, Total Power



OH58 Rig: Three-Way ANOVA

Source of Variation	DF	40% Torque Sum of Squares	40% Torque Percent Total SS		80% Torque Sum of Squares	80% Torque Percent Total SS		100% Torque Sum of Squares	100% Torque Percent Total SS	
Main Effects	5	2.171	40.86	*	18.743	93.34	*	24.425	96.72	*
PHASE	3	1.054	19.84	*	13.77	68.57	*	23.954	94.85	*
LIFT	1	0.877	16.51	*	4.946	24.63	*	0.001	0.00	
BEND	1	0.239	4.50	*	0.027	0.13	*	0.471	1.87	*
2-Way Interactions	7	0.532	10.01	*	0.913	4.55	*	0.641	2.54	*
PHASE LIFT	3	0.433	8.15	*	0.516	2.57	*	0.517	2.05	*
PHASE BEND	3	0.021	0.40		0.115	0.57	*	0.04	0.16	*
LIFT BEND	1	0.078	1.47		0.281	1.40	*	0.083	0.33	*
3-Way Interactions	3	0.009	0.17		0.091	0.45	*	0.01	0.04	
PHASE LIFT BEND	3	0.009	0.17		0.091	0.45	*	0.01	0.04	
Explained	15	2.711	51.03	*	19.746	98.33	*	25.075	99.29	*
Residual	176	2.602	48.97		0.335	1.67		0.179	0.71	
Total	191	5.313	100.00		20.081	100.00		25.254	100.00	

Accounting for Significant Baseline Vibrational Changes

- Results give insight into variation of baseline vibration signatures due to regular maneuvering and routine actions
- This variation and its various sources need to be accounted for before implementing HUMS systems
- Research effort in group to separate out baseline variation sources including nonstationary torque and rpm effects (DTSA)
- Research effort to develop monitoring metrics needed for false alarm evaluation

Time-Domain Monitoring via KL Decomposition

- Vibrational data transformed into optimal form using dimensional reduction via Karhunen-Loeve (KL) transformation (similar to PCA)
- Monitoring KL eigenvectors: eigenvalues (variance) and KL coefficients (weights for each eigenvector)
- Changes in main eigenvectors and residuals indicative of failures and defects
- Ongoing research to compare different helicopter baseline signatures using this method
- Other research effort in group to model baseline changes by means of eigenvectors trained on baseline data (with Marianne Mosher)

KL Decomposition Fundamentals

Characteristic eigenvector equation: $\Sigma_X \times V = V \times D$

Orthonormality condition: $V^T \times V = I$

Eigenvalues and eigenvectors:

$$D = \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \qquad V = \begin{bmatrix} V_1 & V_2 & \cdots & V_n \end{bmatrix}$$

Time-Domain Monitoring via Variance Decomposition

- Power spectrum decomposed into individual power (variance) values (Parseval's theorem)
- Main vibrational frequencies separated out by engineering knowledge (gear mesh, harmonics & sidebands for each gear set)
- Residual indicative of potential changes due to failures and defects
- Ongoing research to determine effectiveness of this method for false-alarm evaluation
- Ongoing research to compare with other metrics requiring more processing

Flight Data Variance Analysis & Decomposition Fundamentals

$$MS = (RMS)^2 = \mu^2 + \sigma^2 = \sum_{i=0}^{N/2} P_i$$

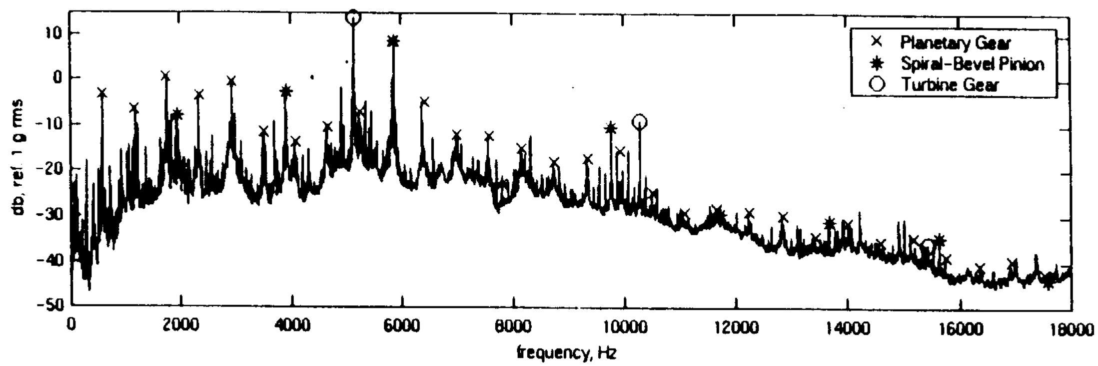
$$\mu^2 = P_0 = 0$$

$$MS = (RMS)^2 = \sigma^2 = \sum_{i=1}^{N/2} P_i = \sum_{i=1}^{N/2} \sigma_i^2$$

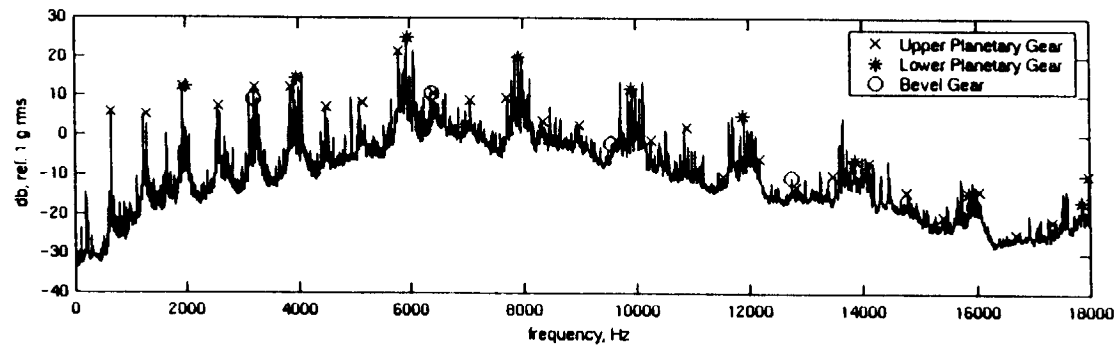
$$\sigma_{Source}^2 = \sum_{i \ni Source} P_i = \sum_{i \ni Source} \sigma_i^2$$

$$df_{Source} = 2 \sum_{i \ni Source} df_i$$

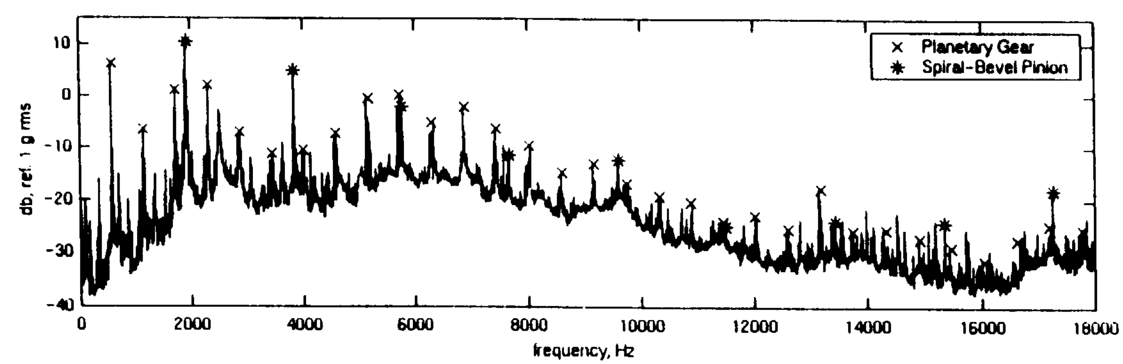
Example: Comparison of Spectra



OH58 Kiowa



AH1 Cobra



OH58 Test rig

Example: Preliminary Flight Variance Decomposition Results

Source	OH-58c Aircraft Average 4 Radial Channels			OH-58c Test Rig Sensor #3 Radial		
	Variance (MS)	df	Percent Total MS	Variance (MS)	df	Percent Total MS
Planetary	17.98	70	17.48	23.38	70	13.79
Pinion - Gear	15.86	18	15.42	30.14	18	17.77
Engine	22.29	6	21.68			
Residual Variance	46.70	8098	45.42	116.07	8104	68.44
Total Mean Square (MS)	102.83	8192	100.00	169.59	8192	100.00

Source	AH-1 Cobra Aircraft Average 3 Triaxial Channels		
	Variance (MS)	df	Percent Total MS
Upper Planetary	691.89	60	5.59
Lower Planetary	1376.99	12	11.12
Pinion - Gear	64.72	10	0.52
Residual Variance	10247.73	8110	82.77
Total Mean Square (MS)	12381.33	8192	100.00

Triaxial Vibration Analysis & Directionality Monitoring

- Vibration measured using triaxial accelerometers to capture more information
- Each direction contains information specific to sub-components and failures and hence provides a more complete picture of changes and can be monitored individually
- Triaxial data transformed into optimum directions via PCA rotation
- Eigenvalues and angles of principal components monitored for directionality changes
- Ongoing research to determine effectiveness for false-alarm evaluation

Example: Preliminary Triaxial Analysis Fundamentals & Results

$$X_{input} = [X \quad Y \quad Z]$$

Input is vibration data in three directions, OH58 flight tests, TSP data, n=512, flight1, file 4, maneuver FFLS

$$LAT = \begin{bmatrix} 365.16 \\ 40.96 \\ 14.83 \end{bmatrix}$$

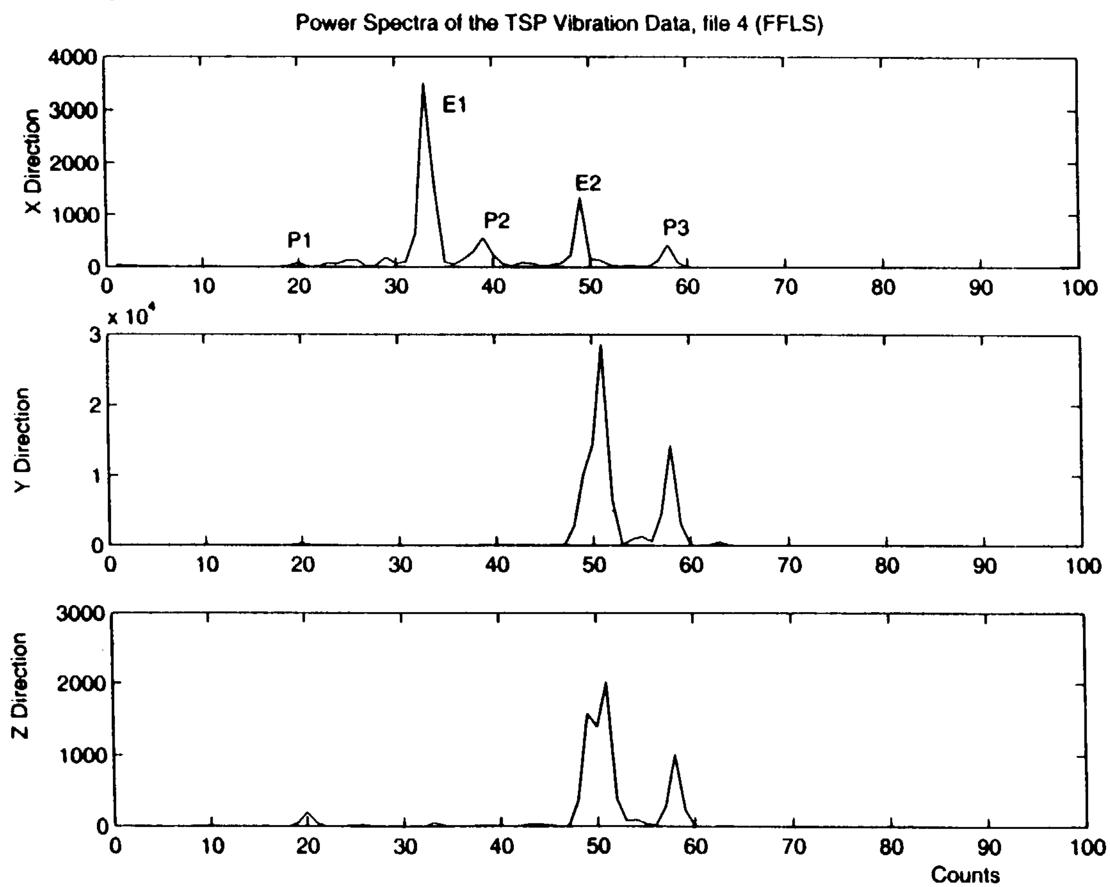
86.8% of variance

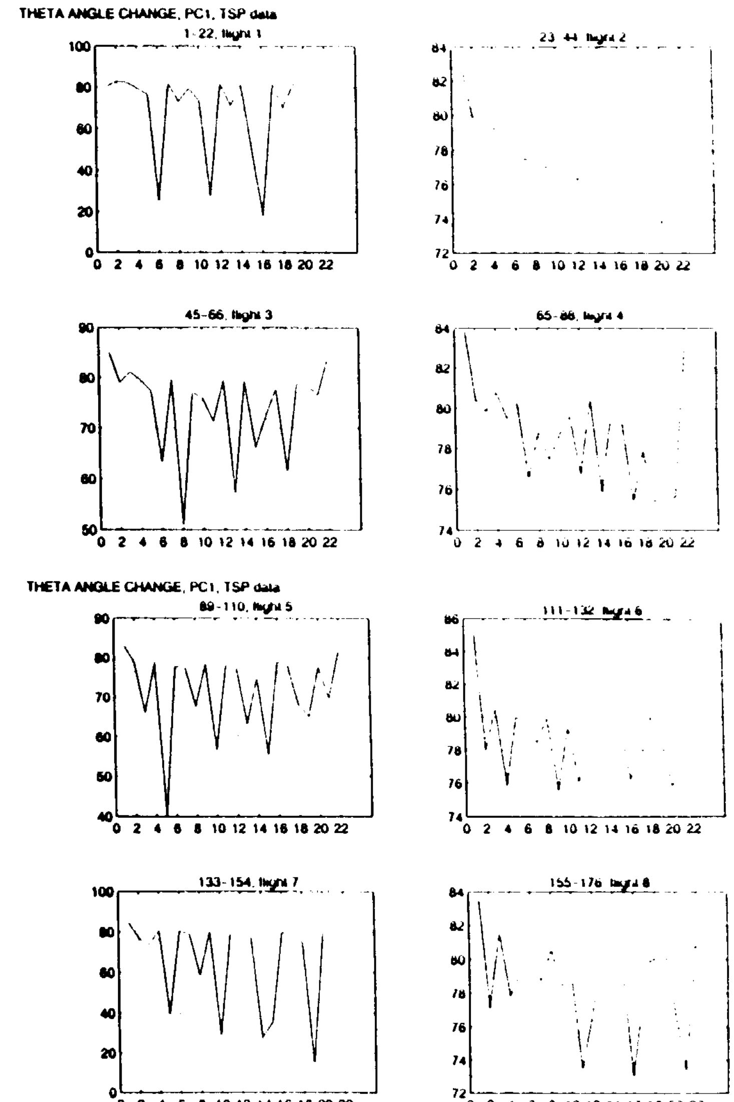
$$PC = \begin{bmatrix} 0.1324 & -0.9142 & -0.3830 \\ 0.9680 & 0.2024 & -0.1486 \\ -0.2133 & 0.3510 & -0.9117 \end{bmatrix}$$

$$SC_1 = 0.1324 \cdot X + 0.9680 \cdot Y - 0.2133 \cdot Z$$

$$\begin{cases} \theta = \arctan(pc(2,1) / pc(1,1)) \cdot 180 / \pi \\ \alpha = \arctan(pc(3,1) / pc(1,1)) \cdot 180 / \pi \end{cases}$$

Example: Triaxial Analysis Results





Design & Manufacturing Variations

- Variation:
  - a major source of failures, scrap, delays, and high costs during part production, and performance & safety problems during operation
  -
    - from manufacturing processes and material defects (ex: bearing inner race surface waviness)
  -
    - from design specifications, tolerances, and tradeoffs (ex: planetary gear spacing)

On-Going D&M Research

- Objective:

  Feed all variation, failure, defect information into design and manufacturing stages early-on to prevent performance and safety problems

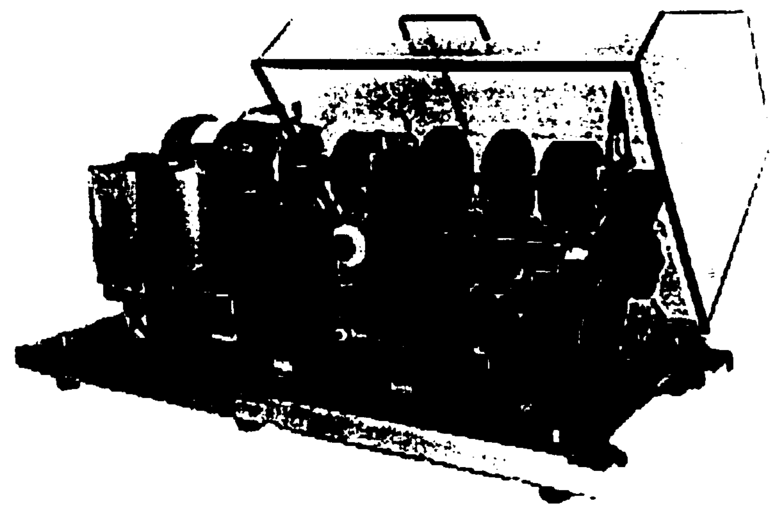
- Planned Output:
  - Formalized methods for D&M
- Current Work:
  - Method to establish empirical/analytical correlations
  - Method to propagate design variations into performance & safety using functional models
  - Methods to capture function-failure similarity & tradeoffs

Manufacturing Variations

- [illegible]
  - Surface roughness, waviness, form error
- [illegible]
  - Surface defects, voids, scratches, burns
- [illegible]
  - Operator errors, tolerance stack-up
- [illegible]
  - Bearings, gears, shafts, rotors,...
- [illegible]
  - Fatigue failure, excessive vibrations, noise
- [illegible]
  - Correlate variations to performance parameter

MFS Experiments

- [illegible] capability:
  - replace components in rotating machinery to test variations in vibrational signature
    - Normal Components
    - Defective Components
- [illegible]
  - Manufacturing errors
  - Assembly errors
  - Design errors?

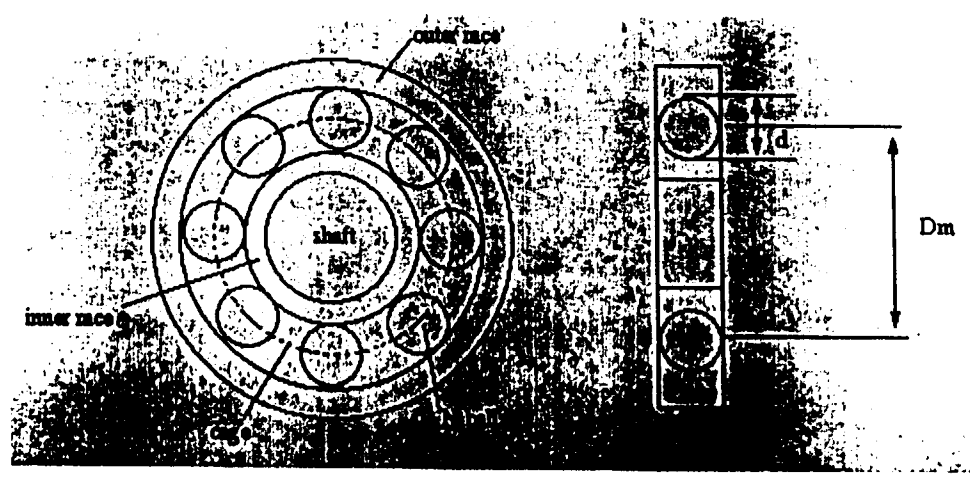


Example: Preliminary Experiments using Bearings

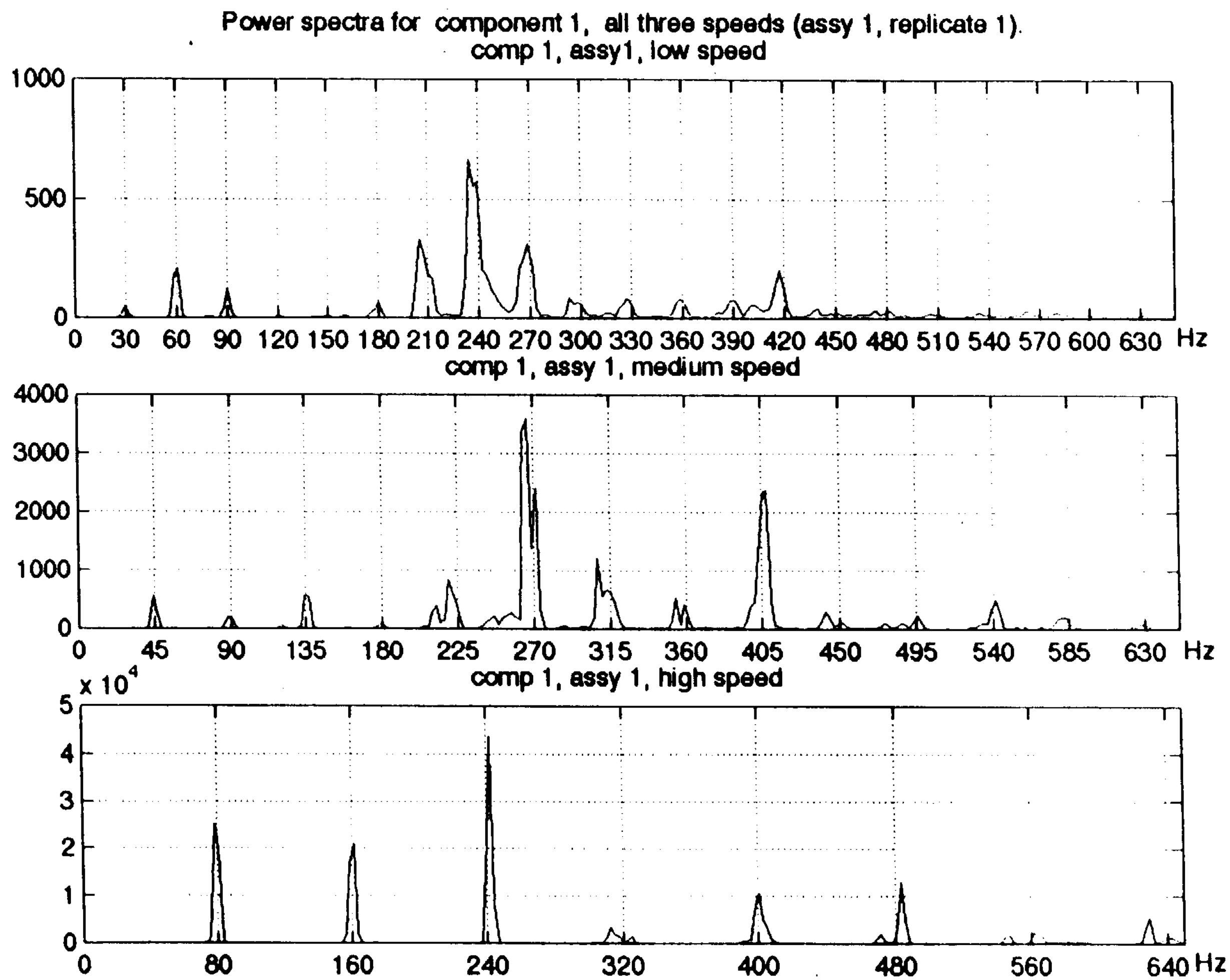
Bearing Defect Frequencies (Hz):

F*shaft*	F*outer*	F*inner*	F*ball* / F*cage*
30	89.93 x K	150.1 x K, 30	112.2 x K, 11.24
45	134.9 x K	225.1 x K, 45	168.3 x K, 16.86
80	239.8 x K	400.2 x K, 80	299.3 x K, 29.98

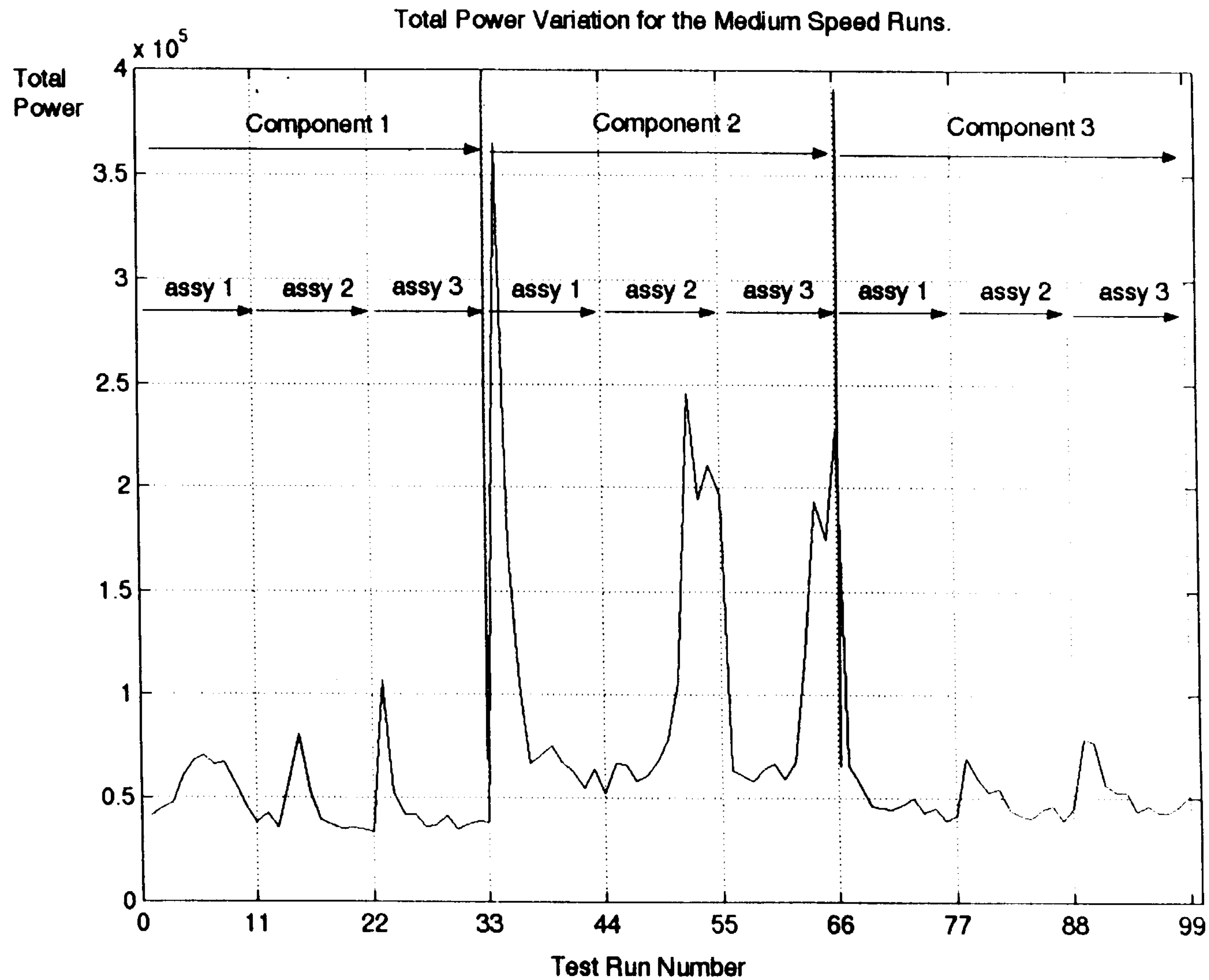
Ball bearing:



Power Spectral Analysis Results



Variation in Total Power



Analysis of Statistical Variance

Source	SS	F	Sig.
Intercept	37221.74	4047.49	.000
Speed	454.17	101.34	.001
Assy	.807	1.43	.510
Component	18.22	4.15	.117
Sp*Assy	1.46	.90	.505
Sp*Comp	9.12	5.62	.019
Assy*Comp	1.27	.78	.565
Sp*Assy*Comp	3.24	3.19	.002

Design Variations

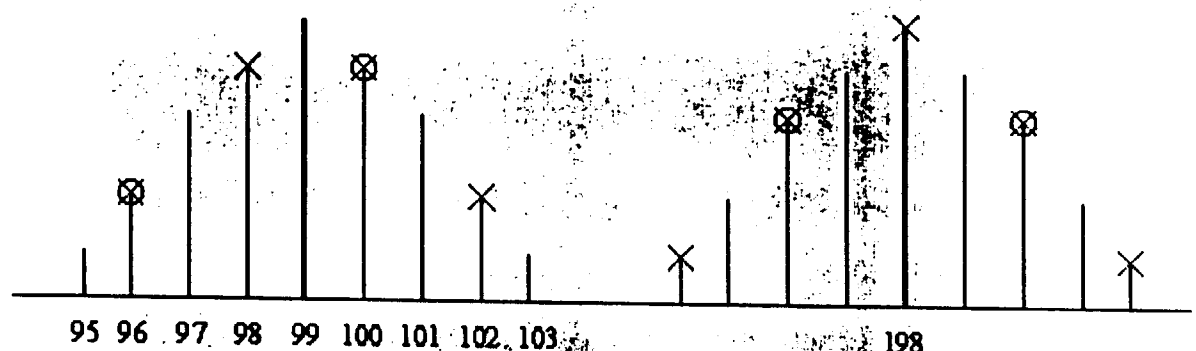
- Problem:
  - Inherent variations (controllable & uncontrollable) propagate from conceptual design (equations) to customer at operating stage (performance, quality, safety)
- Potential Sources:
  - Geometric tolerances
  - Factors of safety
  - Cost trade-offs
- Solution:
  - Method to compute potential variation from design equations and propagate to derive effect on performance using performance equations

Example: Planetary Gear Spacing Variations

- [illegible]lem:
  - Geometric tolerances vary for planetary gear spacings
- [illegible]ator:
  - Vibration signal separation dependent on the exact separation; sidebands appear, false alarm
- [illegible]ion:
  - Estimate and propagate this variation to predict effect on vibration signature

Example: Effect of Design Variation on Performance (Vibration Spectra)

Typical Frequency Distribution from an epicyclic gear set (time-synchronously averaged):



Black: a single planet gear (ideal) ---> planet gear with 99 teeth, sidebands, and harmonics

Red: 2 sets of equally spaced planets ---> multiples of 2

Blue: 4 equally spaced planets ---> multiples of 4

The variation in the spacing of planetary gears in an epicyclic gear system for the OH58 transmission results in the incorrect identification of the frequency components, hence causing potential false alarms during health and safety monitoring.

Failures and Defects Caused by Design Variations

- Problem:
  - Potential failures important to detect at the design stage to avoid performance and safety problems
- Hypothesis:
  - Failures common at the elemental functional level & have similarities that can be used by designers
- Solution:
  - Methods to account for design tradeoffs and similarities using function-failure correlation
  - Function-failure methods will be developed and applied to helicopter failures and components

Example: Failure-Function Method for Tradeoff Analysis in Design

$$CF = \begin{bmatrix} 1 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 \end{bmatrix} \qquad EC = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

C1=gear
C2=bearing
C3=shaft

F1=wear
F2=fatigue
F3=corrosion
F4=fretting
F5=impact

E1=change ME
E2=guide ME
E3=transfer ME
E4=position ME
E5=stabilize ME

$$PC = \begin{bmatrix} \boxed{\begin{matrix} .39 \\ -.47 \\ .47 \\ .39 \\ -.47 \end{matrix}} & \begin{matrix} -.58 & .04 & .70 & .00 \\ -.32 & -.57 & .03 & -.57 \\ .32 & -.78 & .04 & .20 \\ -.58 & -.04 & -.70 & .00 \\ -.32 & -.21 & .01 & .78 \end{matrix} \end{bmatrix}$$

$$SC = \begin{bmatrix} \boxed{\begin{matrix} -0.21 \\ 1.22 \\ -1.00 \end{matrix}} & \begin{matrix} -0.71 & 0.00 & 0.00 & 0.00 \\ 0.25 & 0.00 & 0.00 & 0.00 \\ 0.46 & 0.00 & 0.00 & 0.00 \end{matrix} \end{bmatrix}$$

$$LAT = \begin{bmatrix} 1.27 \\ 0.39 \\ 0.00 \end{bmatrix}$$

76.46% of variance in 1st PC

Pc1= .39 F1 - .47 F2 +.47 F3 + .39 F4 - .47 F5

Shows significance of
effect of each failure mode on the 1st PC

Sc1= -.21 C1 + 1.22 C2 - 1.00 C3

1st PC has the most effect on component 3

Example: Function-Failure Method for Similarity Analysis in Design

Function-Failure Matrix:

$$EF = EC \times CF = \begin{array}{c} \text{Fi} \longrightarrow \qquad \text{Ei} \downarrow \\ \begin{bmatrix} 1 & 1 & 0 & 1 & 1 \\ 1 & 2 & 0 & 1 & 2 \\ 1 & 2 & 0 & 1 & 2 \\ 1 & 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 \end{bmatrix} \end{array}$$

Failures F2 & F5 occur more frequently for functions E2 & E3

Functions E2 & E3 experience same failure modes

Functions E4 & E5 experience same failure modes

Component-Failure Similarity Matrix:

$$\Lambda_{CF} = CF \times CF^T = \begin{bmatrix} 4 & 2 & 2 \\ 2 & 3 & 0 \\ 2 & 0 & 2 \end{bmatrix}$$

C1 shares 2 common failures modes with C2 & C3

C2 & C3 share no common failure modes

Diagonal gives the count of failure modes per component

$$\Lambda_{FC} = CF^T \times CF = \begin{bmatrix} 2 & 1 & 1 & 2 & 1 \\ 1 & 2 & 0 & 1 & 2 \\ 1 & 0 & 1 & 1 & 0 \\ 2 & 1 & 1 & 2 & 1 \\ 1 & 2 & 0 & 1 & 2 \end{bmatrix}$$

Etc...similar uses with EC and FC...

Conclusions and Future Plans

- Operational variations
  - Status: flight and phase 1 rig tests & statistical analyses complete
  - On-going work: more flights; crack tests; triaxial analysis; monitoring metrics; false alarm evaluation
- Design & manufacturing variations
  - Status: preliminary mfg experiments; failure-function method
  - On-going work: failure-function method; variation propagation for performance
- Publications: http://[illegible]/director[illegible]
- Collaborators:
  - Dr. Edward Huff, NASA Ames Research Center
  - Dr. Marianne Mosher, NASA Ames Research Center
  - Dr. David Lewicki, NASA Glenn Research Center
  - Dr. Robert Stone, Univ. of Missouri-Rolla
  - Dr. Todd Leen, Oregon Graduate Institute

Overall Goal: Feedback of Variation Info into Design